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SOME EFFECTS OF UPLAND DISCHARGE ON ESTUARINE HYDRAULICS

by Henry B. Simmons

HYDRAULICS DIVISION

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EXPLANATORY STATEMENT

At the Fall Convention of the ASCE at New York, N. Y., in 1954, the Hydraulics division presented a symposium on tidal hydraulics. Papers of this symposium, so far published in Proceedings are:

"Tide Heights Along the Coasts of the United States," by L. P. Disney. (Proc. Paper 666, April 1955)

"Tidal Computations in Shallow Water," by J. J. Dronkers and J. C. Schonfeld. (Proc. Paper 717, June 1955)

"Computation of Tides and Tidal Currents – United States Practice," by H. A. Einstein and R. A. Fuchs. (Proc. Paper 715, June, 1955)

"Tidal Currents at Inlets in the United States," by Joseph M. Caldwell. (Proc. Paper 716, June 1955)

"Estuarine Circulation Patterns," by D. W. Pritchard. (Proc. Paper 717, June 1955)

"Engineering Problems in U.S. Tidal Waterways," by J. H. Douma. (Proc. Paper 789, September 1955)

"Some Effects of Upland Discharge on Estuarine Hydraulics," by Henry B. Simmons. (Proc. Paper 792, September 1955)

SOME EFFECTS OF UPLAND DISCHARGE ON ESTUARINE HYDRAULICS

Henry B. Simmons[1]

Engineers concerned with the solution of problems in estuarine environments have become keenly aware in recent years that the amount of fresh water discharged into an estuary, and the degree to which it mixes therein with the salt water of the sea, are major factors in establishing the hydraulic and shoaling regimens of the estuary involved. For the purpose of this paper, the writer will illustrate the role of upland discharge in establishing estuary mixing type, describe a simplified method for determining the most significant hydraulic characteristic of estuaries, and demonstrate the effects of changing the upland discharge into estuaries on their hydraulic characteristics. Although estuarine sedimentation is not a principal matter of concern in this paper, the writer will discuss certain broad relationships between estuary hydraulic and shoaling phenomena. Interpretations of data and opinions expressed herein are those of the writer and are not necessarily those of the Corps of Engineers.

Estuaries are semi-inclosed bodies of water, freely connected with the sea, and most estuaries receive fresh-water runoff from upland drainage areas. As a result they contain both salt and fresh water in varying amounts, since the fresh water entering the upstream end of the estuary must eventually find its way to the sea and since the more dense salt water tends to force its way upstream, usually underneath the fresh water but mixed with the fresh water in some degree. The water in the upstream reach of an estuary is fresh or nearly so, while that near the entrance consists largely of sea water.

The presence in estuaries of waters of variable density causes marked differences in the magnitudes, distributions, and durations of the currents as compared to those of a single density system. The source of the heavier salt water is at the seaward end of the estuary and that of the fresh water is at the upstream end. As a result of the density difference, each type of water tends to assume a rough wedge shape with the base of the wedge at the source and the point away from the source. The interface of (or line of demarkation between) the salt and fresh water may vary from well-defined to almost obscure, depending on the degree of mixing of the salt and fresh water in any given estuary. Where the mixing is slight the transition from fresh to salt water is well defined and occurs within a small percentage of the channel depth. On the other hand, where the mixing is appreciable no definite interface of the salt and fresh water exists except in isolated instances.

Knowledge of the degree of mixing of salt and fresh water in an estuary is highly important to the investigator concerned with the solution of estuarine problems, since this phenomenon appears to control certain important

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features of the hydraulic and shoaling characteristics of an estuary. For convenience, the degree of mixing may be separated into three broad categories of highly stratified, partly mixed, and well mixed, but the transition from one type of mixing to another is gradual instead of well defined. In the subsequent paragraphs, the writer will illustrate some of the most important characteristics of the highly-stratified, partly-mixed, and well-mixed estuaries through the use of current velocity and salinity data obtained in South west Pass of the Mississippi River, Savannah Harbor, and the Delaware Estuary.

In all estuaries in which there is significant stratification of the salt and fresh water, the magnitudes, durations, and directions of the currents above the interface are appreciably different from those below. Fig. 1 shows schematically the distribution of current velocities and directions in a highly-stratified estuary of which Southwest Pass of the Mississippi River provides an excellent example. Upstream from the tip of salt-water intrusion, the direction of flow throughout the entire depth is toward the sea at all times with a vertical velocity distribution similar to that of an upland stream. Farther downstream the flow in the fresh-water strata is still toward the sea, but the direction of flow in the underlying salt water is upstream at all times. The cause of the continuous upstream flow within the salt-water strata, even though the extent of salt-water intrusion may be stable, is constant erosion of salt water from the interface by the outflowing fresh water. The salt water thus eroded must be replaced to maintain stability of the intrusion length, and so a continuous upstream current is generated beneath the interface.

The lengths of the flow direction arrows in fig. 1 indicate the relative magnitudes of currents throughout the highly stratified estuary. Maximum velocities in the fresh-water strata occur near the surface and near the entrance to the estuary, while the maximum currents in the salt-water strata occur near the bottom and near the upstream limit of intrusion. Generally speaking, velocities in the fresh water decrease with distance from the surface and those in the salt water decrease with distance from the bottom, with the result that a point of zero velocity is found in the vicinity of the interface.

The left portion of fig. 2 shows the normal vertical distribution of salinity from surface to bottom in the highly-stratified estuary. It will be noted that the transition from fresh to salt water occurs very quickly and in a small percentage of the channel depth. The right portion of fig. 2 shows the normal vertical distribution of current velocities at a point upstream from the limit of salt-water intrusion and at a point within the region of intrusion. The velocity distribution upstream from the limit of intrusion is quite similar to that of an upland stream, while the distribution at the downstream point indicates downstream flow above the interface and upstream flow beneath the interface.

Rapid shoaling usually occurs in the region of the salt-water intrusion tip in a highly stratified estuary. The heavier particles of sediment, which are rolled or pushed along the river bed by the outflowing fresh water, come to rest as soon as the tip of intrusion is reached. The lighter particles, which are transported largely in suspension in the fresh water, gradually fall through the interface along the length of intrusion and are transported upstream by the salt-water currents to the vicinity of the tip. The channel reach occupied by the upstream limit of intrusion is therefore a focal point for accumulation of sediment from both upstream and downstream, with the heavier particles depositing just upstream from the intrusion limit and the lighter particles just downstream.

Fig. 3 shows schematically the distribution of current velocities and directions in a partly-mixed estuary, which is the most common type found in nature. Typical examples of the partly-mixed estuary are the Hudson River, Charleston and Savannah Harbors, and the St. Johns River. The interface in the partly-mixed estuary is not so well defined as that in the highly-stratified type, but it can be detected easily by either salinity or current velocity measurements. The interface in the partly-mixed estuary moves upstream and downstream as the tide floods and ebbs, usually over a distance of several miles. Although the currents in both the fresh-water and salt-water strata usually reverse with tidal phase, the downstream currents in the fresh-water strata are much stronger than the upstream currents, while the upstream currents in the salt water strata are stronger than the downstream currents. As in the case of the highly-stratified estuary, the maximum currents in the fresh water are usually near the surface and near the estuary entrance, while those in the salt-water strata are usually near the bottom and near the upstream limit of salt water intrusion.

The left portion of fig. 4 shows the typical vertical distribution of salinity at high tide and low tide in a partly-mixed estuary; the horizontal difference between the two curves indicates the change in salinity with tidal phase at a given point in the vertical. These curves indicate that the salinity at the bottom is appreciably greater than at the surface, especially at low tide, and that the greatest change in salinity from surface to bottom occurs in about 20 per cent of the total depth. The right portion of fig. 4 shows the typical vertical distribution of current velocities at a station located upstream from the limit of salt water intrusion and at one located well down in the saline region of the estuary. At the upstream station, the direction of flow reverses with tidal phase but the velocity distributions, both flood and ebb, are essentially the same as in an upland stream. The ebb velocities at this station are somewhat greater than the flood velocities, depending on the amount of fresh water entering the upstream end of the estuary. At the downstream station, ebb velocities at the surface are much greater than flood velocities while flood velocities at the bottom are appreciably greater than ebb velocities. Also, because of the greater density of the water in the lower strata, the reversal in flow from ebb to flood occurs much earlier at the bottom than at the surface with the result that the duration of the bottom flood current exceeds that of the bottom ebb current. At the surface the duration of the ebb current exceeds that of the flood because the fresh water is exhausted from the estuary principally in the surface strata.

The region of heaviest shoaling in the partly-mixed estuary usually lies between the high tide and low tide positions of the upstream limit of saline intrusion as indicated in fig. 3. As in the case of the highly-stratified estuary, the heavier particles of sediment come to rest when they reach the intrusion limit. The lighter particles may be carried well down into the estuary before they enter the predominantly upstream flow in the lower strata, but they are then transported back upstream to the vicinity of the intrusion limit. There is little evidence of sorting of the sediment particles in the partly-mixed estuary, since the intrusion limit moves back and forth over an appreciable distance with tidal phase which permits intermingling of the sediment particles.

Fig. 5 shows schematically the distribution of current velocities and directions in the well-mixed estuary, of which the Delaware and Raritan Estuaries provide typical examples in nature. The mixing of salt and fresh water is of a high degree in this type of estuary, with the result that a definite interface does not exist except in rare instances. However, surface

salinities are somewhat less than bottom salinities at any given location. and careful analysis of current velocity measurements will usually show characteristics similar to those of the partly-mixed estuary though much less prominent. Ebb velocities predominate over flood velocities in the upper strata, but flood velocities usually predominate slightly over ebb velocities at the bottom. A cursory examination of current velocity measurements made in a well-mixed estuary will usually leave the impression that ebb currents predominate over flood currents at all depths, but a detailed analysis of the velocity data, by methods which will be discussed subsequently in this paper, will show that the normal distribution of flow is similar to that shown schematically in fig. 5.

The left portion of fig. 6 shows the typical distribution of salinity from surface to bottom in the well-mixed estuary at high tide and low tide. It will be noted that the rate of change in salinity from surface to bottom is nearly constant; a rapid change at some critical depth is not evident as in the case of the partly-mixed estuary. However, bottom salinities are usually some 15 to 25 per cent greater than surface salinities, and this difference is sufficient to affect the vertical distribution of current velocities to some extent.

The right portion of fig. 6 shows the typical vertical distribution of current velocities in the well-mixed estuary, both at a location upstream from the limit of salt-water intrusion and at a location well within the salt-water region of the estuary. The distribution of currents at the upstream station is identical with that for a similar location in the partly-mixed estuary, since both are in the fresh-water portion of the estuary and unaffected by density differences. At the downstream station, surface velocities are appreciably stronger during ebb than flood while bottom velocities are slightly stronger during flood than ebb. The characteristics of the velocity distribution in the well-mixed estuary are therefore almost identical with those of the partly mixed type, the difference between the two being almost completely in the degree of density effect. In other words, the greater the density differences from surface to bottom, or more properly stated the greater the degree of stratification, the greater the distortion of the vertical velocity distribution from that found in upland streams.

Since the effects of density differences on the vertical distribution of currents are small in the well-mixed estuary, the distribution of shoaling in this type does not appear to be directly related to the limits of salinity intrusion except in isolated instances. The locations of shoals in the well-mixed estuary appear to be influenced more by such factors as excessive cross-sectional area, nonuniform flow caused by islands and divided channels, and other physical features than by the limits of salinity intrusion.

It is emphasized that the characteristics of a particular estuary in nature may not be identical with any one of the three types used for illustration in the foregoing paragraphs, since the specific estuary may fall anywhere in the range from highly stratified to almost completely mixed. This paper is concerned primarily with the effects of mixing of salt and fresh water on the hydraulics of estuaries; so let us consider first the role of upland discharge in establishing the estuary's mixing type. It is the writer's opinion that the two principal factors that dictate whether an estuary is highly stratified, partly mixed, or well mixed are (a) upland discharge, and (b) turbulent mixing of fresh and salt water in the estuary by tidal action. We normally find the highly-stratified estuary where the upland discharge is large with respect to the tidal forces, the partly-mixed estuary where both the upland discharge

and the tidal forces are fairly large, and the well-mixed estuary where the upland discharge is small with respect to the tidal forces.

The mean tidal prism of an estuary (defined as the volume of water flowing into the estuary from the sea during an average flood-tide period) provides a fair index to its tidal forces, and the writer has found from experience that the ratio of mean upland discharge into an estuary (defined as the volume of upland water entering an estuary for conditions of mean upland discharge and over the interval of a mean tidal cycle of about 12.42 hours) to its mean tidal prism is a fairly dependable index to its mixing type. Where the ratio is of the order of 1.0 or greater (average for Southwest Pass of the Lower Mississippi River is about 1.25), we normally find the highly-stratified type; where the ratio is of the order of 0.25 (average for Savannah Harbor is about 0.20), we normally find the partly-mixed type; and where the ratio is appreciably less than 0.1 (average for the Delaware Estuary is about 0.01), we normally find the well-mixed type. This ratio should be used only in a very general way, since there is evidence that one reach of a given estuary may be partly mixed while another reach may be well mixed for identical conditions of tide and upland discharge, but it does provide a quick and fairly dependable means for predicting estuary mixing type in the absence of detailed measurements of current velocities and salinities.

If we can assume that upland discharge into an estuary plays an important role in dictating whether it will be highly stratified, partly mixed, or well mixed, then the importance of prior knowledge indicating the effects of changing the upland discharge into an estuary is obvious. For example, an existing partly-mixed estuary may be changed to well mixed by reducing the upland discharge, or it may be changed to highly stratified by increasing the upland discharge. Since information available to the writer indicates that the pattern of shoaling in estuaries varies with type of mixing, it follows that estuarine sedimentation is an important effect of upland discharge.

In considering the effects of changes in upland discharge on the hydraulics of an estuary, and in turn on its shoaling characteristics, the investigator is confronted with a large number of factors that may be used for analysis; for example, a change in upland discharge may be considered in terms of its effects on maximum flood or ebb velocities, mean flood or ebb velocities, duration of flood or ebb currents, etc. But the investigator finds it very difficult to interpret the effects of changes in upland discharge on any one hydraulic factor in terms of change in shoaling characteristics. The sediments that cause shoaling in estuaries consist largely of flocculated clays and other fine-grain materials which, once placed in suspension, are transported readily by very weak currents. Experience with shoaling in estuaries, especially in navigation slips and dead-end channels, has led the writer to the opinion that such sediments will be transported anywhere that water goes. For this reason, establishment of a single criterion to define the hydraulic characteristics of an estuary, and one that can be used in turn to define the principal features of its resulting shoaling pattern, is very important to the engineer charged with the solution of hydraulic and shoaling problems in estuaries.

Within the past few years, the writer has developed a method for analyzing current velocity measurements made in estuaries that offers promise as a means for defining the hydraulic characteristics of an estuary in simple terms, describing the broad features of the accompanying shoaling pattern, and predicting with fair accuracy the effects of proposed changes in upland discharge or tidal prism on hydraulic and shoaling characteristics. In essence, this method reduces a combined analysis of the velocities, directions, and durations of the currents into a single expression, and that

expression defines whether the predominant flow at any given location and depth is toward the ocean or from the ocean and in what percentage of the total flow at the point in question. Let us say that current velocity measurements are made at 10 per cent increments of depth at a given station over a complete tidal cycle. A conventional plot of velocity versus time for each point in the vertical is then made. The areas subtended by both the flood and ebb curves of the plot are planimetered, and the total area thus determined provides an index to the total flow at the point of measurement. The area subtended by the ebb curve is then divided by the combined areas of the flood and ebb curves, and the resultant determines what percentage of the total flow at the point of measurement is downstream or toward the ocean. From the value thus determined from each point in the vertical, a second plot is constructed to define the distribution of flow from surface to bottom for the vertical in question. It is emphasized that the plot described above does not represent the distribution of discharge from surface to bottom, since the cross-sectional area of the channel does not enter into the computation. Rather, the plot defines the direction and degree of predominance of flow from surface to bottom at the vertical in question.

Let us use Savannah Harbor, roughly mapped in fig. 7, to illustrate the value of this method of analysis. Fig. 8 presents flow predominance curves for various locations in Savannah Harbor. Field data used in this analysis were obtained for conditions of mean tide and a normal low fresh-water discharge (5,670 cfs). Flow distribution curves for stations 92 and 109, which are upstream from the tip of the salt-water wedge for all or most of the time, indicate that more than 50 per cent of the flow is downstream at all depths. At station 130, which is in the upstream limit of salt-water intrusion all or most of the time, flow is predominantly upstream in the bottom 10 to 15 per cent of the channel depth and predominantly downstream in the remaining 85 to 90 per cent of the depth. At all other stations, which are downstream from the intrusion limit at all times, flows are predominantly downstream from the surface to about middepth and are predominantly upstream from about middepth to the bottom.

Fig. 9 presents a different method for plotting the results of the above-described analysis. In this figure, the percentage of total flow downstream at surface and bottom for each station is plotted against channel stations. The resultant curves indicate those regions of the harbor in which the currents at the depths under consideration are predominantly upstream or downstream and in what degree.

Study of the flow distribution curves in figs. 8 and 9 has led the writer to the following conclusions: (a) for the conditions of tide and upland discharges considered in this analysis, sediment entering the upstream end of Savannah Harbor is moved progressively downstream at all depths to the vicinity of station 130; (b) sediments transported by the bottom strata will be deposited in the vicinity of station 130, since the predominance of upstream flow along the bottom throughout the remainder of the harbor will prevent further movement of such sediments toward the sea; (c) sediments carried by the upper strata will be transported toward the sea, but a major portion of these sediments will sink into the bottom strata during intervals of slack current and will be carried upstream to the vicinity of station 130 by the predominant upstream flow in the bottom strata. Therefore, for the above conditions of tide and upland discharge, the reach of channel in the vicinity of station 130 and upstream therefrom should be subject to a very high shoaling rate if these data can in fact be used to predict the location of major shoals.

Maintenance dredging records for Savannah Harbor indicate that by far the largest shoal in the harbor is located at and upstream from station 130, and it has been determined that the rate of shoaling in this reach of channel is greatest for fresh-water discharges of the same order of magnitude as that occurring at the time of the field velocity measurements used in the above analysis. Greater or smaller fresh-water discharges will shift the location of the point of zero predominance of bottom flow (50 per cent total flow downstream) in the harbor and thus shift the area of most rapid shoaling. The writer has been informed that a few years ago the fresh-water discharge into Savannah Harbor was held at about 20,000 cfs for a period of several months by operation of the outlet works at Clark Hill Dam, and it was noted that no shoaling occurred in the vicinity of station 130 during the entire period, especially in the upstream portion of the shoal area.

As a second example of the usefulness of the above-described method of analysis, and one chich will demonstrate that different portions of the same estuary may be well mixed and partly mixed for identical conditions of tide and upland discharge, let us consider the case of Carquinez Strait in the San Francisco Bay system (see fig. 7). Carquinez Strait is about 8.2 miles long, has an average width of about 0.75 miles, has mean depths ranging from about 40 to 90 ft., and is the only connection between San Pablo Bay to the west and Suisun Bay to the east. Almost all of the fresh water entering the bay system is introduced by the Sacramento and San Joaquin Rivers to the east of Carquinez Strait and therefore must pass through the strait. Field data used in the analyses described below were obtained for conditions of mean tide and a fresh-water discharge of about 25,000 cfs.

Fig. 10 presents curves showing the vertical distribution of flow for Crockett cross section in the westerly end of the strait and Benicia in the easterly end. At Crockett, the flow is predominantly downstream in the upper third of the depth and predominantly upstream in the lower two thirds, while at Benicia the flow is predominantly downstream throughout the complete depth. Since the volume of fresh water passing both of these points during a tidal cycle is the same, the difference in flow distribution must be attributed to great turbulence produced by tidal current velocities in the strait which effectively mixes the salt and fresh water and thus prevents stratification. At Crockett, however, the density difference between the mixed water of the strait and the salt water of San Pablo Bay is sufficient to cause stratification in the westerly end of the strait and thus result in a vertical flow distribution characteristic of the partly-mixed estuary.

The characteristics of the flow distribution curves in fig. 10 indicate that the westerly end of Carquinez Strait should accumulate light-weight sediments, since such sediments would be moved predominantly downstream throughout the full depth in the easterly end of the strait and be trapped by the predominantly upstream flow throughout the bottom two-thirds of the depth at the westerly end. Tidal current velocities in Carquinez Strait proper are much too great to permit significant deposition of light sediments; however, Mare Island Strait joins Carquinez Strait near its westerly end and is the location of the most serious shoaling problem in the San Francisco Bay system. Maintenance dredging records indicate that an average of about 3,000,000 cu yd of material per year must be dredged from Mare Island Strait to maintain an adequate navigation channel to the Mare Island Navy Yard. In the opinion of the writer, the vertical distribution of flow in and adjacent to the westerly end of Carquinez Strait is largely responsible for the great amount of shoaling in Mare Island Strait through provision of an

almost unlimited supply of sediment at the entrance to the strait.

The obtaining of sufficient prototype data to show how the flow distribution of a given estuary is affected by upland discharge over a wide range of conditions is a very difficult undertaking. Such data may be obtained readily and economically by means of hydraulic models, but for the purpose of this particular paper the writer prefers to use prototype data only. Fortunately, a series of current velocity measurements were made in Savannah Harbor a few years ago, and data obtained at one point were sufficiently complete to permit a detailed analysis of flow distribution over a wide range of upland discharge. The results of this analysis, which show the predominance of flow at surface, middepth, and bottom for upland discharges ranging from a low of about 3,000 cfs to a high of 66,000 cfs, are shown in fig. 11.

The flow distribution curves in fig. 11 indicate that for zero upland discharge the flow is almost exactly 50 per cent downstream and 50 per cent upstream at all depths. Without upland discharge, there is no predominance of flow in either direction at any depth, because there is no possibility of stratification. As the upland discharge increases, flow in the surface strata is more and more predominantly downstream until, at an upland discharge of about 40,000 cfs, the direction of flow in the surface strata is downstream throughout the tidal cycle. At middepth, the percent of total flow downstream increases from 50 to about 55 as the upland discharge increases from zero to about 10,000 cfs. Flow in these strata remains about 55 per cent downstream until that in the surface strata is 100 per cent downstream, following which there is a sharp increase in the predominance of downstream flow at middepth. For an upland discharge of 66,000 cfs, flow in the middepth strata is about 75 per cent downstream. At the bottom, the percentage of total flow downstream decreases sharply from 50 per cent at zero upland discharge to a minimum of about 25 per cent for an upland discharge of about 20,000 cfs. Further increases in upland discharge above 20,000 cfs gradually increase the percentage of downstream flow in the bottom strata; however, for a discharge of 66,000 cfs the total flow downstream in the bottom strata is only about 43 per cent, as compared to 50 per cent for zero discharge.

The upland discharges into many estuaries have been modified in recent years by the construction and operation of dams and reservoirs for flood control, generation of electric power, irrigation, municipal water supply, and other purposes, and many more such modifications are planned for the future. In some instances, significant quantities of upland discharge have been diverted from one watershed to another with the result that the upland discharge into one estuary may be increased while that into another may be reduced. Reservoir operation for any purpose usually results in a reduction of peak upland discharges and an increase in low discharges. It is the opinion of the writer that serious shoaling problems may have been created, and the severity of other already existing shoaling problems may have been increased, by changing the upland discharges into estuaries without due consideration of the effects of such changes on resulting hydraulic and shoaling conditions.

On the basis of analyses and discussions presented in the foregoing paragraphs of this paper, the writer has arrived at the following general conclusions:

a. The degree of mixing of salt and fresh water in estuaries plays an important role in establishing their hydraulic regimens. Since it has been demonstrated that the shoaling remimens of some estuaries are related directly to their hydraulic regimens, it follows that the degree of mixing also plays

an important role in establishing their shoaling regimens.

b. Because of incomplete mixing of salt and fresh water in estuaries, the predominance of flow in the bottom strata is almost always upstream while that in the surface strata is downstream; the degree of such predominance is dependent on the degree of mixing, being most prominent in the highly-stratified estuary and least prominent in the well-mixed type.

c. Changes in the upland discharge, tidal prism, and physical configurations of estuaries will frequently change the degree of mixing of salt and fresh water therein and thus affect such important features as the vertical distribution of current velocities, the direction and degree of flow predominance, the amount of shoaling, and the location of major areas.

d. Available data indicate that light-weight sediments are supplied to estuaries principally through the medium of upland discharge. It therefore follows that upland discharge plays a dual role in the problem of estuarine sedimentation, since a large portion of the potential shoaling material is supplied by one of the three principal contributors to the resultant hydraulic regimen.

e. The magnitude of changes in upland discharge into estuaries usually far exceeds that of changes in tidal prism or physical configuration. For this reason, and because upland discharge is of primary importance, it follows that major changes in upland discharge should be accomplished only after consideration of all probable effects.

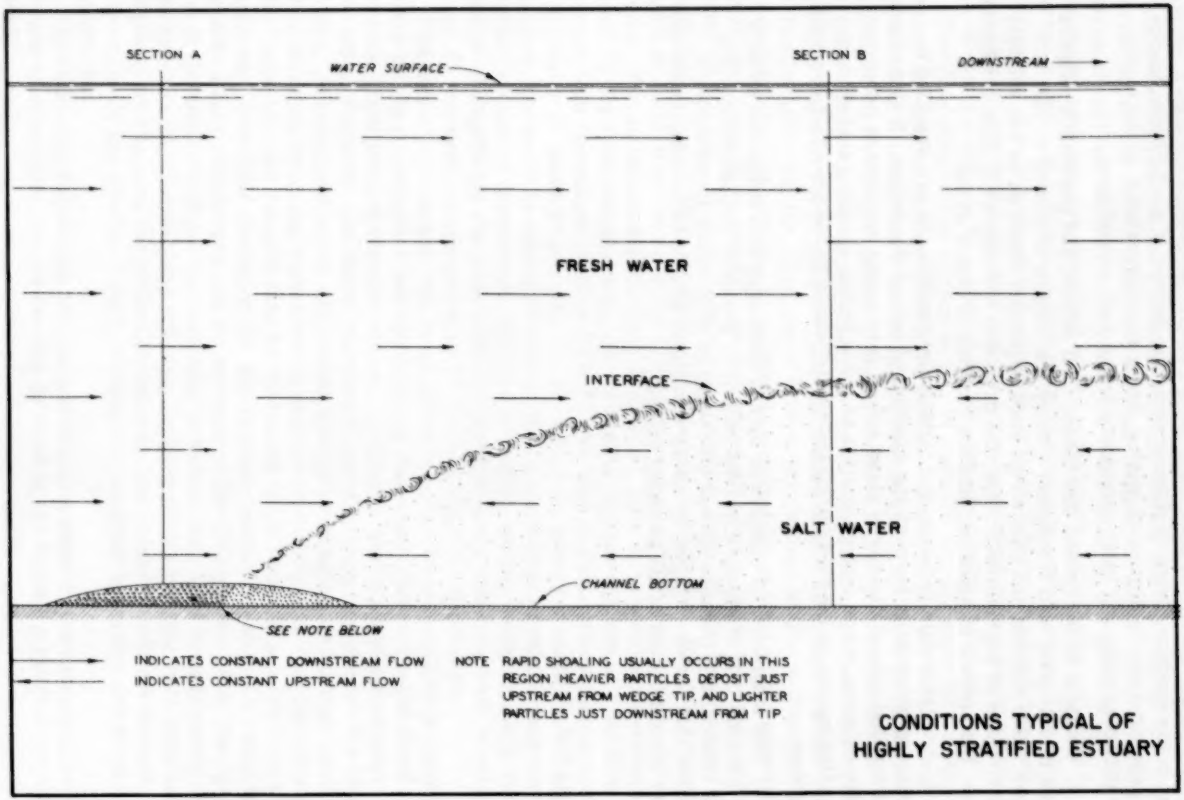
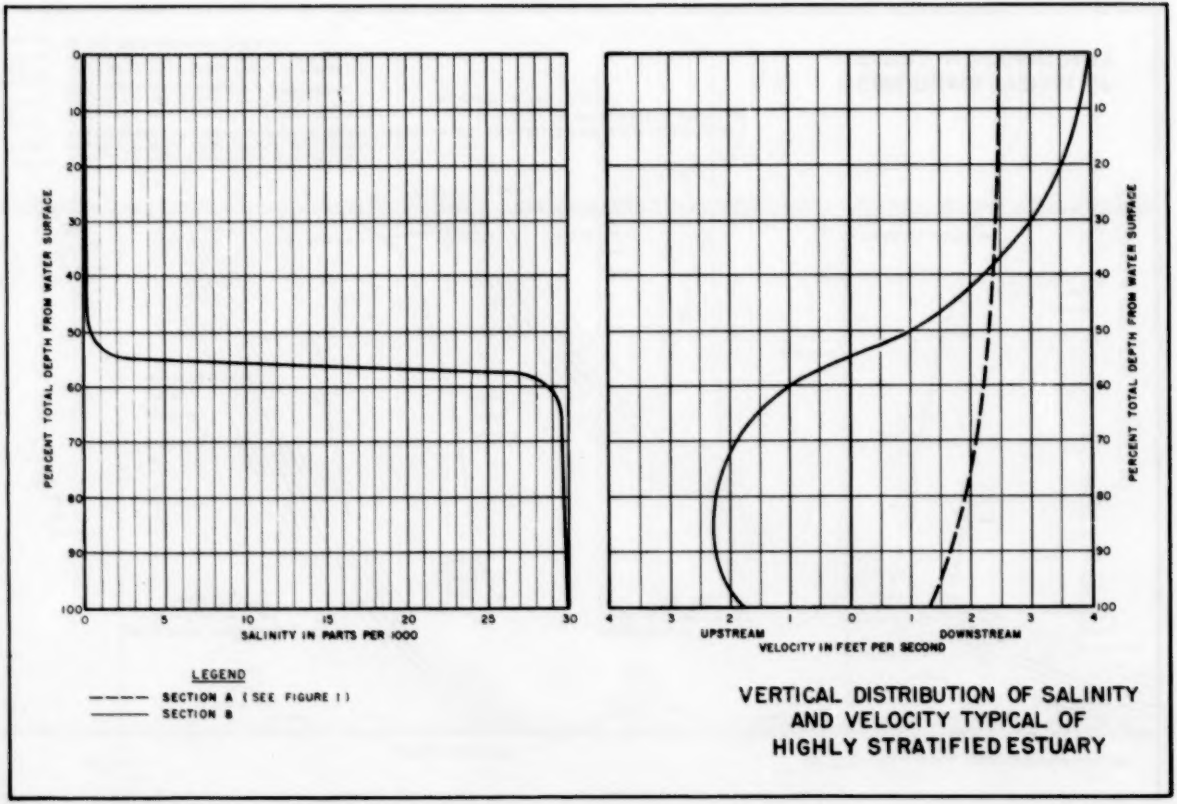

SECTION A
WATER SURFACE
SECTION B
DOWNSTREAM
FRESH WATER
INTERFACE
SALT WATER
CHANNEL BOTTOM
SEE NOTE BELOW
INDICATES CONSTANT DOWNSTREAM FLOW
INDICATES CONSTANT UPSTREAM FLOW
NOTE RAPID SHOALING USUALLY OCCURS IN THIS REGION HEAVIER PARTICLES DEPOSIT JUST UPSTREAM FROM WEDGE TIP, AND LIGHTER PARTICLES JUST DOWNSTREAM FROM TIP
CONDITIONS TYPICAL OF HIGHLY STRATIFIED ESTUARY

FIGURE 1

792-10



VERTICAL DISTRIBUTION OF SALINITY AND VELOCITY TYPICAL OF HIGHLY STRATIFIED ESTUARY

FIGURE 2

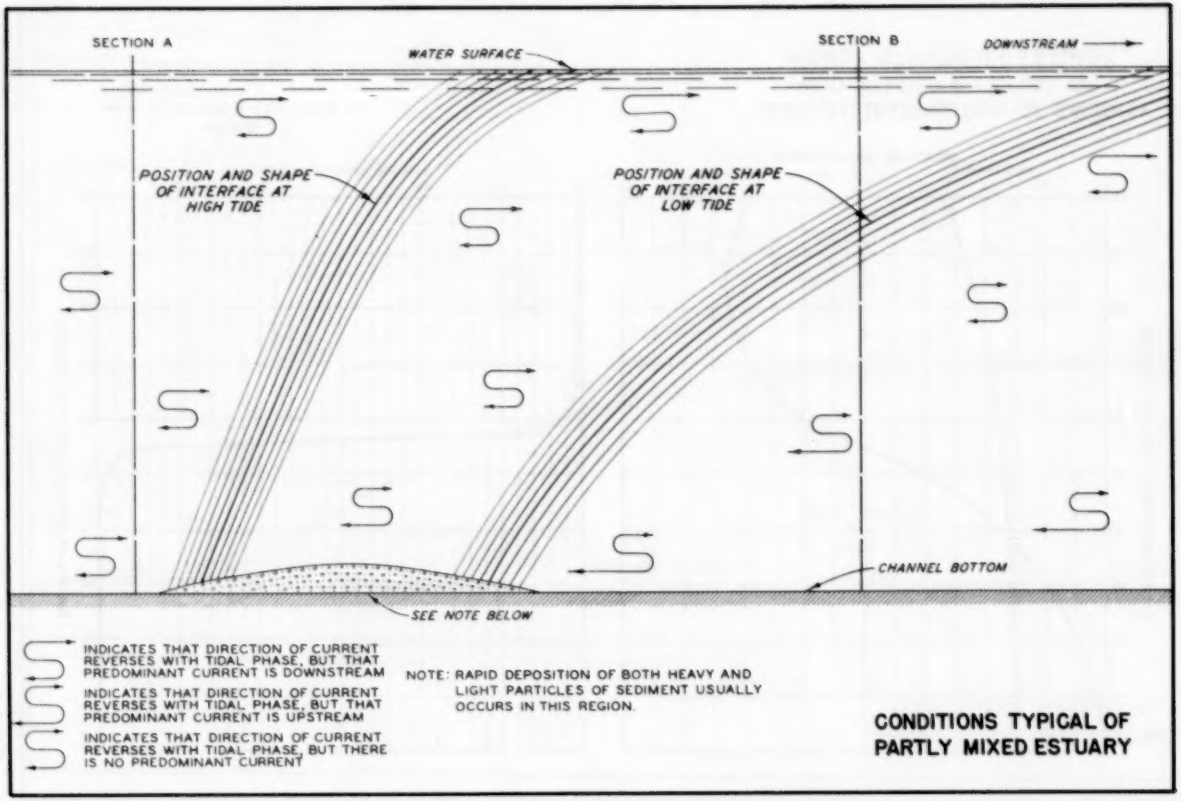
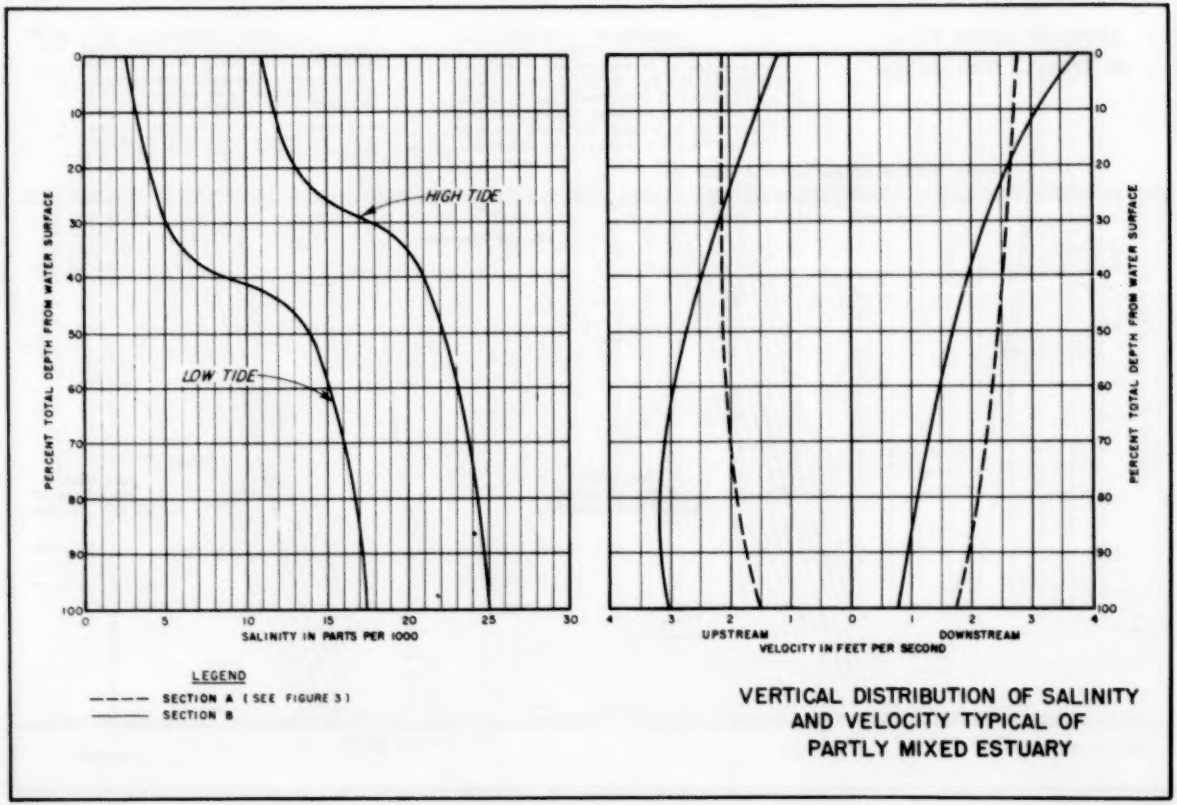

SECTION A
WATER SURFACE
SECTION B
DOWNSTREAM
POSITION AND SHAPE OF INTERFACE AT HIGH TIDE
POSITION AND SHAPE OF INTERFACE AT LOW TIDE
CHANNEL BOTTOM
SEE NOTE BELOW
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THAT PREDOMINANT CURRENT IS DOWNSTREAM
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THAT PREDOMINANT CURRENT IS UPSTREAM
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THERE IS NO PREDOMINANT CURRENT
NOTE: RAPID DEPOSITION OF BOTH HEAVY AND LIGHT PARTICLES OF SEDIMENT USUALLY OCCURS IN THIS REGION.
CONDITIONS TYPICAL OF PARTLY MIXED ESTUARY

FIGURE 3

792-12



VERTICAL DISTRIBUTION OF SALINITY AND VELOCITY TYPICAL OF PARTLY MIXED ESTUARY

FIGURE 4

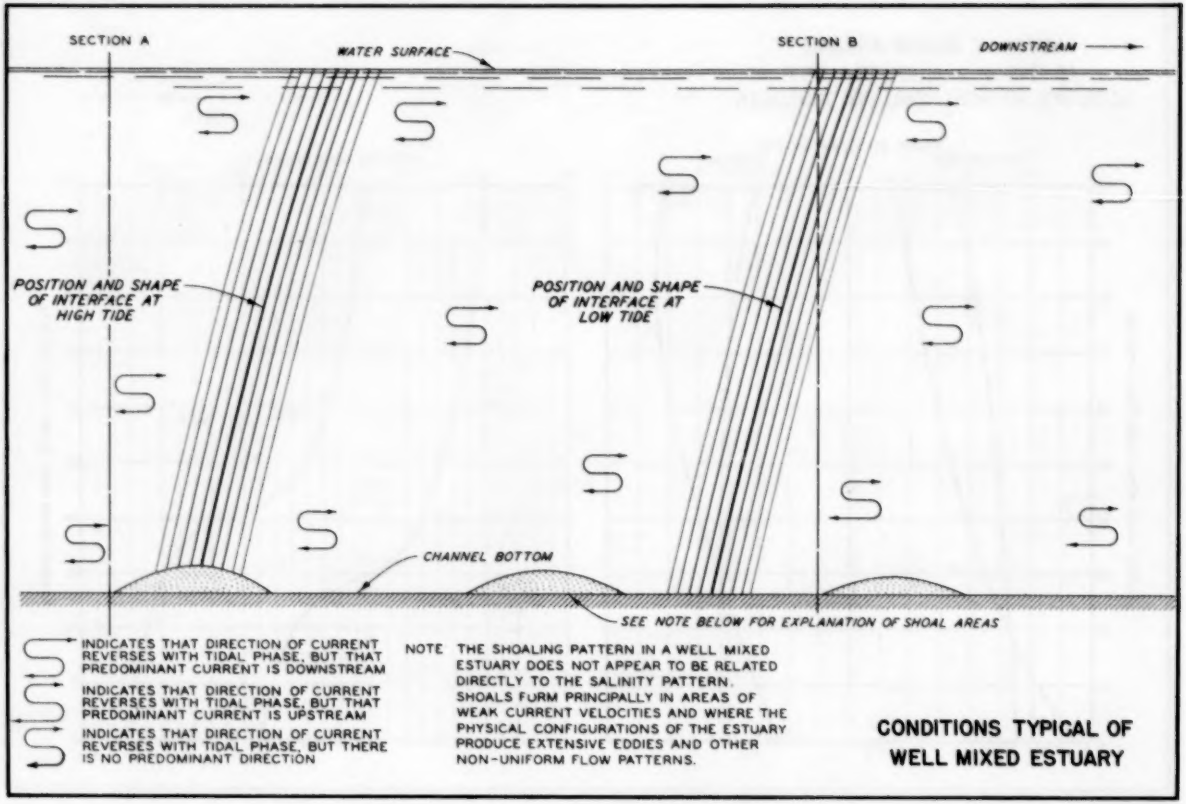
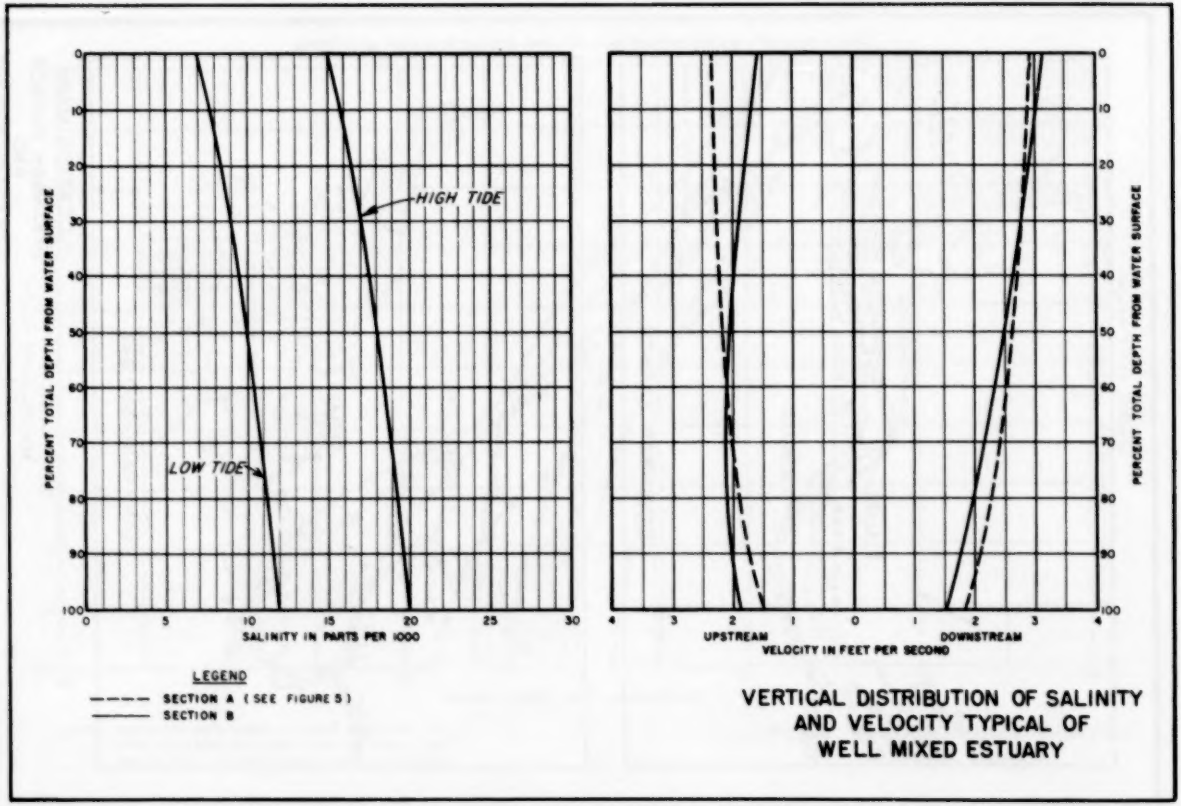
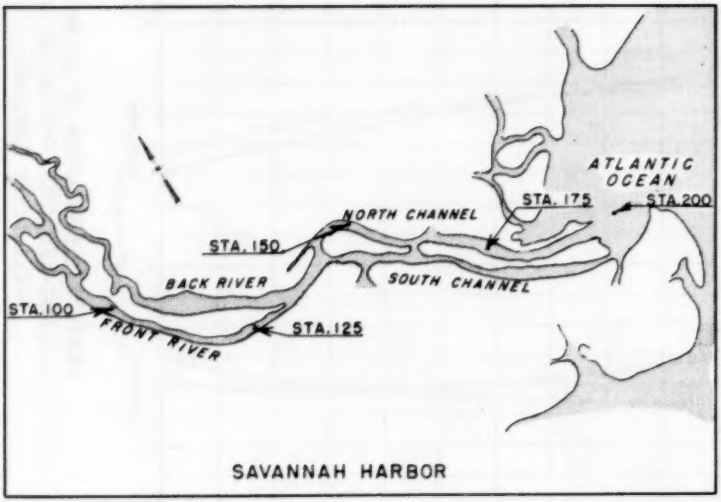

SECTION A
WATER SURFACE
SECTION B
DOWNSTREAM
POSITION AND SHAPE OF INTERFACE AT HIGH TIDE
POSITION AND SHAPE OF INTERFACE AT LOW TIDE
CHANNEL BOTTOM
SEE NOTE BELOW FOR EXPLANATION OF SHOAL AREAS
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THAT PREDOMINANT CURRENT IS DOWNSTREAM
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THAT PREDOMINANT CURRENT IS UPSTREAM
INDICATES THAT DIRECTION OF CURRENT REVERSES WITH TIDAL PHASE, BUT THERE IS NO PREDOMINANT DIRECTION
NOTE THE SHOALING PATTERN IN A WELL MIXED ESTUARY DOES NOT APPEAR TO BE RELATED DIRECTLY TO THE SALINITY PATTERN. SHOALS FORM PRINCIPALLY IN AREAS OF WEAK CURRENT VELOCITIES AND WHERE THE PHYSICAL CONFIGURATIONS OF THE ESTUARY PRODUCE EXTENSIVE EDDIES AND OTHER NON-UNIFORM FLOW PATTERNS.
CONDITIONS TYPICAL OF WELL MIXED ESTUARY

FIGURE 5



VERTICAL DISTRIBUTION OF SALINITY AND VELOCITY TYPICAL OF WELL MIXED ESTUARY

FIGURE 6

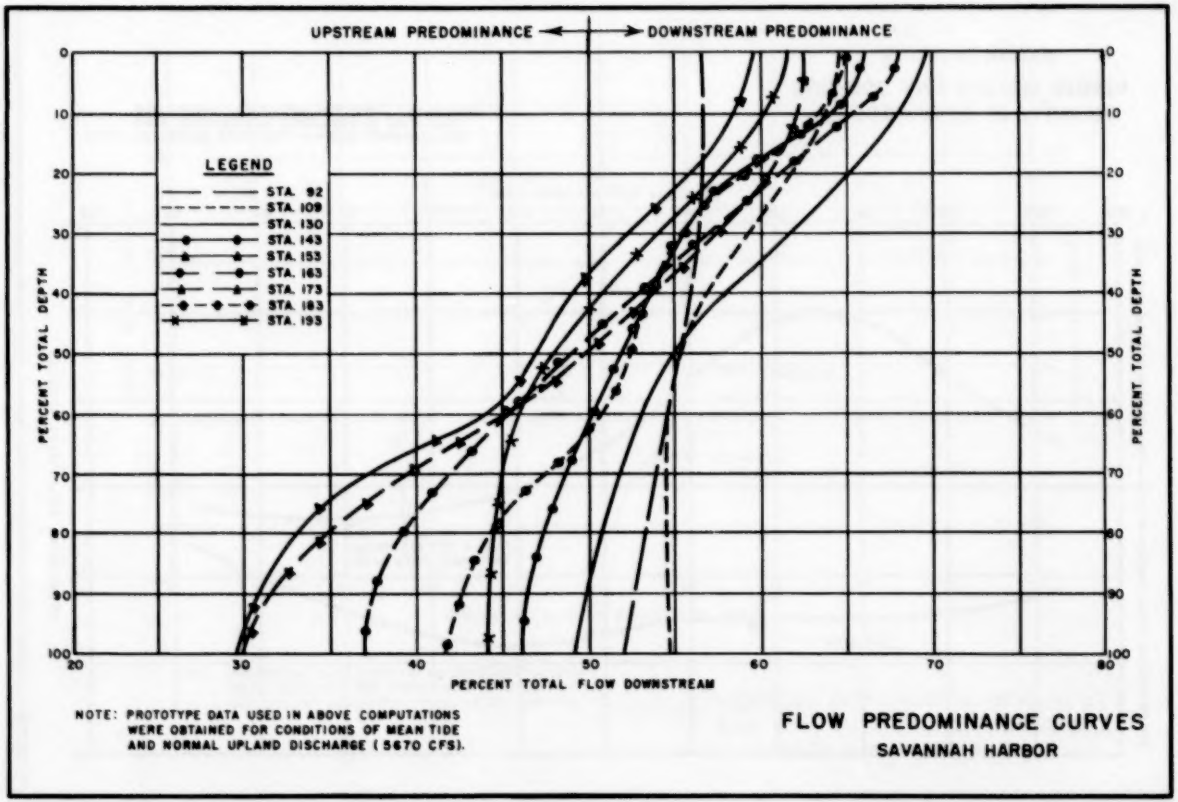


SAVANNAH HARBOR

SAN FRANCISCO BAY

LOCATION MAPS
SAVANNAH HARBOR
AND
SAN FRANCISCO BAY

FIGURE 7



NOTE: PROTOTYPE DATA USED IN ABOVE COMPUTATIONS WERE OBTAINED FOR CONDITIONS OF MEAN TIDE AND NORMAL UPLAND DISCHARGE (5670 CFS).

FLOW PREDOMINANCE CURVES
SAVANNAH HARBOR

FIGURE 8

792-17

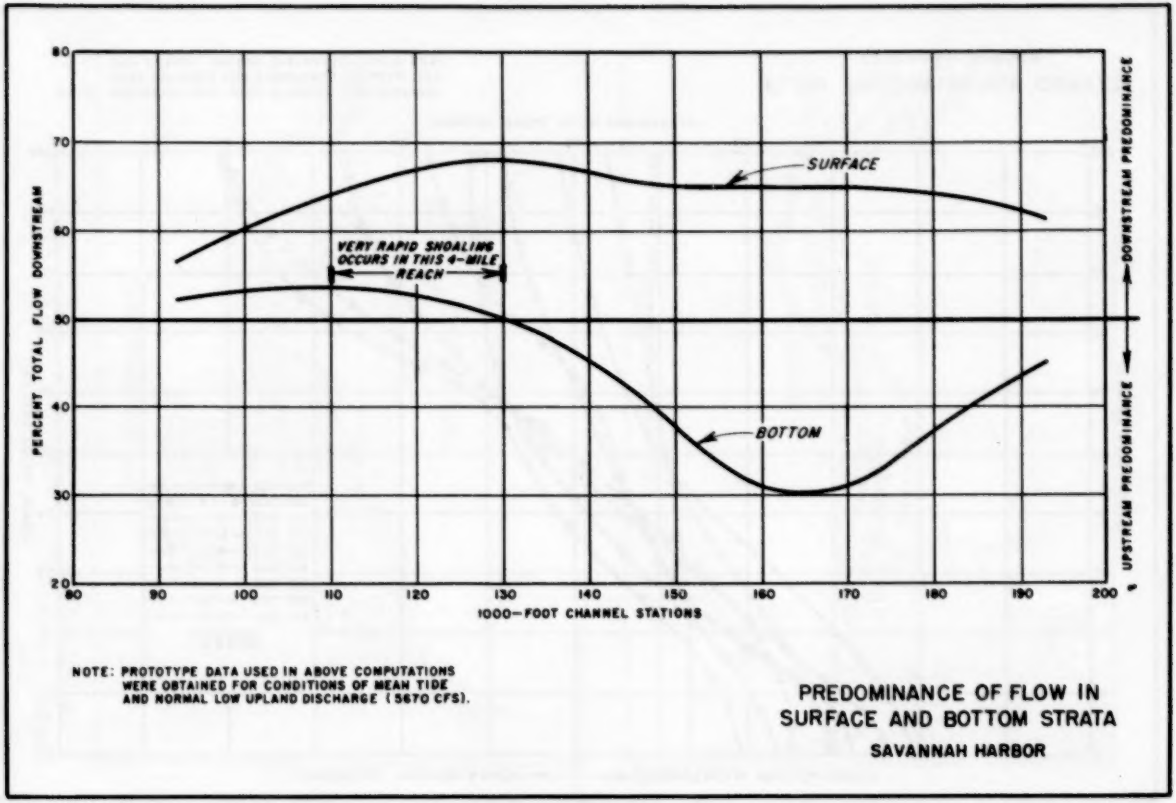
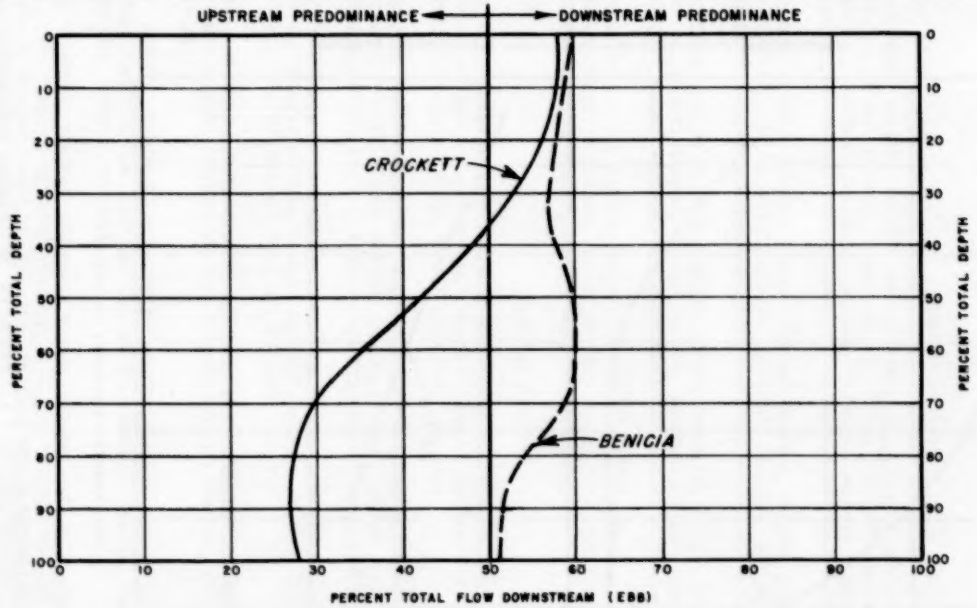

80
70
60
50
40
30
20
PERCENT TOTAL FLOW DOWNSTREAM
SURFACE
VERY RAPID SHOALING OCCURS IN THIS 4-MILE REACH
BOTTOM
80
90
100
110
120
130
140
150
160
170
180
190
200
1000-FOOT CHANNEL STATIONS
DOWNSTREAM PREDOMINANCE
0
UPSTREAM PREDOMINANCE
NOTE: PROTOTYPE DATA USED IN ABOVE COMPUTATIONS WERE OBTAINED FOR CONDITIONS OF MEAN TIDE AND NORMAL LOW UPLAND DISCHARGE (5670 CFS).
PREDOMINANCE OF FLOW IN SURFACE AND BOTTOM STRATA
SAVANNAH HARBOR

FIGURE 9

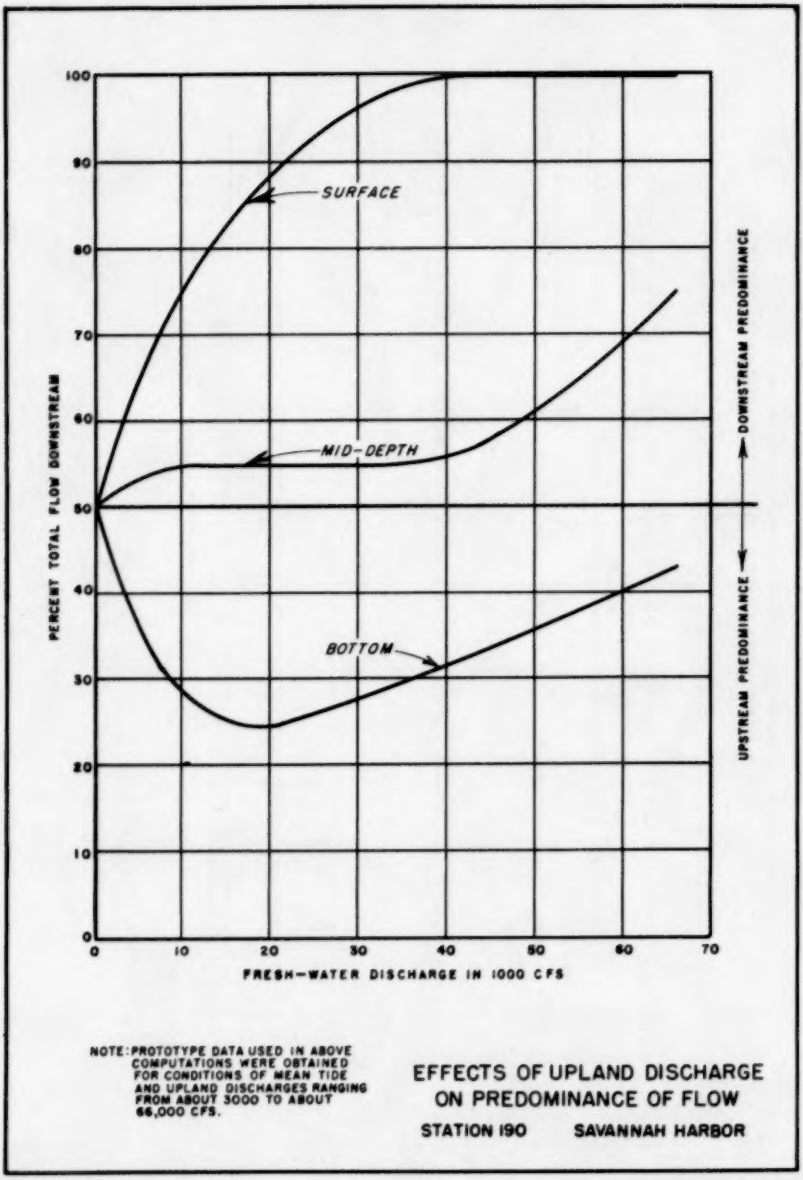


NOTE: PROTOTYPE DATA USED IN ABOVE COMPUTATIONS WERE OBTAINED FOR CONDITIONS OF MEAN TIDE AND UPLAND DISCHARGE OF ABOUT 25,000 CFS.

VERTICAL DISTRIBUTION OF FLOW AT EAST AND WEST END OF CARQUINEZ STRAIT, SAN FRANCISCO BAY

FIGURE 10

792-19



NOTE: PROTOTYPE DATA USED IN ABOVE COMPUTATIONS WERE OBTAINED FOR CONDITIONS OF MEAN TIDE AND UPLAND DISCHARGES RANGING FROM ABOUT 3000 TO ABOUT 66,000 CFS.

EFFECTS OF UPLAND DISCHARGE ON PREDOMINANCE OF FLOW

STATION 190 SAVANNAH HARBOR

FIGURE 11

PROCEEDINGS PAPERS

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

VOLUME 80 (1954)

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

VOLUME 81 (1955)

JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

AUGUST: 761(BD), 762(ST), 763(ST), 764(ST), 765(ST)[c], 766(CP), 767(CP), 768(CP), 769(CP), 770(CP), 771(EM), 772(EM), 773(SA), 774(EM), 775(EM), 776(EM)[c], 777(AT), 778(AT), 779(SA), 780(SA), 781(SA), 782(SA)[c], 783(HW), 784(HW), 785(CP), 786(ST).

SEPTEMBER: 787(PO), 788(IR), 789(HY), 790(HY), 791(HY), 792(HY), 793(HY), 794(HY)[c], 795(EM), 796(EM), 797(EM), 798(EM), 799(EM)[c], 800(WW), 801(WW), 802(WW), 803(WW), 804(WW), 805(WW), 806(HY), 807(PO)[c], 808(IR)[c].

c. Discussion of several papers, grouped by Divisions.

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